Chemical Plume Mapping with an Autonomous Underwater Vehicle

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***Abstract*- A REMUS (Remote Environmental Measuring UnitS) autonomous undersea vehicle (AUV) is being used for chemical plume mapping as part of the Office of Naval Research (ONR) Chemical Sensing in the Marine Environment (CSME) program. Bathymetric, current, temperature and fluorometric data are collected while the vehicle performs a ladder type search across and downstream of a dye source. These data are used to validate and refine an analytical plume model. Operational experiences and data collected will be presented from operations at San Clemente Island, California and Duck, North Carolina.**

I. OVERVIEW

A. Background

The *Chemical Sensing in the Marine Environment (CSME)* program is funded by the Office of Naval Research. It is aimed at developing and demonstrating the effectiveness of advanced technology sensors for detecting explosives and other chemical species of interest in coastal regions of the ocean. In particular, CSME currently is interested in detecting and prosecuting plumes containing trace amounts of explosives that leach into the sea water from man-made objects, such as unexploded ordnance. Progress toward development of this operational system is proceeding along two paths: development of a suitable contaminant sensor able to be taken to the field, and the pursuit of strategic solutions to the critical issues associated with detecting plumes and localizing sources. To address the latter path, the Hydro series of experiments have focused on understanding the plume structure and behavior, using plumes of dye in appropriate real-world ocean environments.

B. Objective

In order to collect data for the plume model, the Woods Hole Oceanographic Institution's (WHOI) REMUS autonomous underwater vehicle was used to gather plume data under differing conditions. To date, this process has been conducted at two sites with differing water and bottom conditions: San Clemente Island, CA and the Field Research Facility at Duck, NC. This data will be used to verify and refine the analytical model of a plume in the water column.

II. EXPERIMENTAL SETUP

A. REMUS Vehicle Configuration

The REMUS vehicle was configured with the standard suite of sensors with the addition of an upward and downward looking acoustic doppler current profiler (ADCP) for velocity field measurements, and a dye fluorometer for dye detection. The latter was installed in a specially modified nose cone, allowing for data collection in an unperturbed flow field. The WHOI long baseline navigation system was used for correlating dye concentration with location information. The REMUS software utilities greatly facilitated the rapid downloading and initial evaluation of the data collected.

Figure 1: REMUS Vehicle configuration

B. Environmental Sensors

In order to get all the data required, a number of other sensors were used in addition to the dye fluorometer. The bathymetry of the area was mapped with side scan sonar, making note of bottom contours and potential obstructions. The current profile was continually measured by an upward and downlooking acoustic doppler current profiler (ADCP). Bottom mounted ADCPs were also used to monitor the current profile near the dye source. Conductivity, temperature, and depth profiles were also monitored near the source to provide a more complete picture of the environmental conditions surrounding the formation of the plume. These were of particular interest to note the differences in the San Clemente and Duck environments.

C. Dye Pumping

Rhodamine dye was pumped into the water through a wound soaker hose arrangement, allowing diffusion of the dye from an area roughly the size of a 50 gallon drum. The plume then developed as a function of the current as shown in Figure 2.

Figure 2: The Plume

III. SAN CLEMENTE OPERATIONS

A. Environmental Conditions

Operations were held at San Clemente Island in March 2001. While the missions performed were predominantly focused on training new operators, significant data was also collected regarding the plume structure and the REMUS operations. Generally speaking, the conditions were calm with a slight wind chop. Water clarity was fair for the island, with a significant amount of runoff due to earlier rains. Currents were low, on the order of 5 cm/sec, but sufficient for plume development. An underwater video was placed near to the source, so that the actual plume development could be observed from shore. The operational area available was roughly 400m x 100m, constrained by the sloping bottom topography and the kelp beds. Due to these obstacles, the REMUS vehicle was generally operated at an altitude of 2-3 m above the bottom.

B. Data Collection

A total of 8 missions were run over a 5 day period, as outlined in Table 1. The focus of the operation was on training and learning the techniques for vehicle operation and data collection. One of the main environmental features of San Clemente is the presence of kelp, both as defined beds and free floating. When the inevitable collisions happened, the vehicle demonstrated several behaviors such as backing and rising to become disentangled. These were often very effective, with the vehicle extricating itself and continuing on with the pre-programmed path, as shown in Figure 3. Plume data was also collected (Figure 4), which served to demonstrate the utility of using the REMUS to collect plume information.

TABLE 1
San Clemente Missions

	Type	Duration (hh:mm)	Comments
1	Ladder: 17 rows intersecting	1:12	Aborted due to kelp entanglement
2	Ladder: 6 rows	0:29	Completed run
3	Ladder: 25 rows	0:46	All dead reckoning due to misrepresented transponder
4	Ladder: 16 rows varying widths	0:58	Completed run despite multiple entanglements
5	Photo passes: 8 ladder: 20 rows	0:40	Completed run
6	Photo passes: 8 ladder: 20 rows	0:44	Timed out due to entanglements
7	Ladder: 32 rows intersecting	0:47	Completed run
8	Ladder: 32 rows intersecting	0:05	Aborted due to entanglements

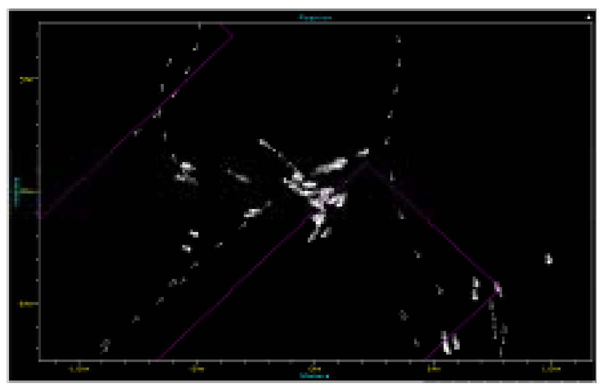

Figure 3: REMUS entanglement track

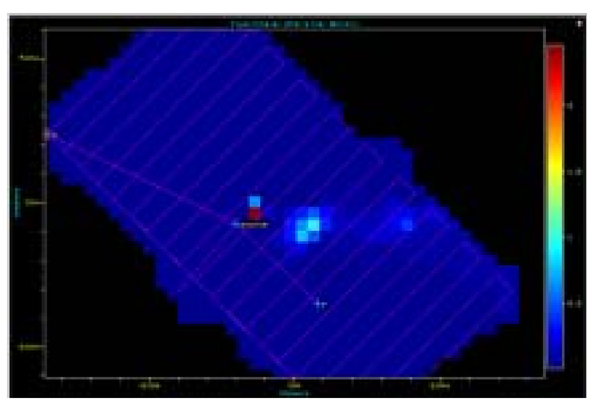

Figure 4: San Clemente plume data

IV. DUCK OPERATIONS

A. Environmental Conditions

In contrast to the San Clemente missions, the Duck operations were focused on plume data collection. The bottom at Duck was a gradual sandy slope, with a flat bottom extending a significant distance at 10 m depth. This allowed for a larger operations area with 2 1000 m x 800 m sections available for use. It also permitted lower altitude operations, down to 1.5 m above the bottom, the limit of the REMUS dead reckoning system. The currents were also significantly higher than San Clemente, ranging from 8-35 cm /sec. As anticipated, weather played a more significant role in operations: 2 days were scrubbed due to sea states too high to launch the rubber boat support craft.

B. Data Collection

Seventeen missions were run over 5 days, collecting a wealth of data on both the plume and the area characteristics (Table 2). Four major types of missions were run at Duck: navigation assessment, fixed-range plume crossings, and ladder searches of both the near and far-field. These are shown in Figure 5.

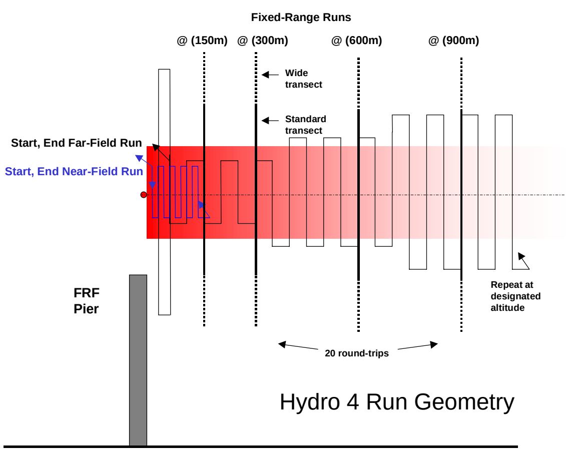

Figure 5: Types of REMUS runs [Morris 2001]

The navigation runs of the vehicle consisted of ten long transects in the onshore / offshore direction. Data from these runs was used to assess the performance of the REMUS long baseline positioning system and to provide calibration information for the dead reckoning system.

The full-field runs were designed to encompass the full extent of the plume up to 1 km from the source. Typically, these runs provided increasingly wider transects (100 m , 200 m, and 300 m wide) of the plume at 50 m spacing. The path was then repeated with a return along the same track as shown in Figure 6.

TABLE 2
Duck Missions

	Type	Time hh:mm	Comments
1	Navigation	1:05	Good Calibration
2	Fixed range: 150 m	2:15	Completed
3	Near field	0:49	Completed
4	Fixed range: 150 m	1:48	Aborted due to weather
5	Far-field: 1 km	1:32	Completed
6	Fixed range: 300 m	1:47	Completed: variable altitude
7	Fixed range: 600 m	1:00	Completed 20 passes
8	Side Scan survey	1:36	High resolution survey of obstructions
9	Side scan survey	2:42	Survey of full area
10	Side scan survey	0:33	Reproducibility check
11	Fixed range: 150 m	1:52	Completed
12	Far field: 1 km	2:18	Completed: wide field
13	Navigation	1:02	Inshore-offshore
14	Navigation	0:40	Along-shore
15	Near field	0:40	Completed
16	Fixed range 150 m	1:29	Completed
17	Fixed range: 430 m	0:59	Competed

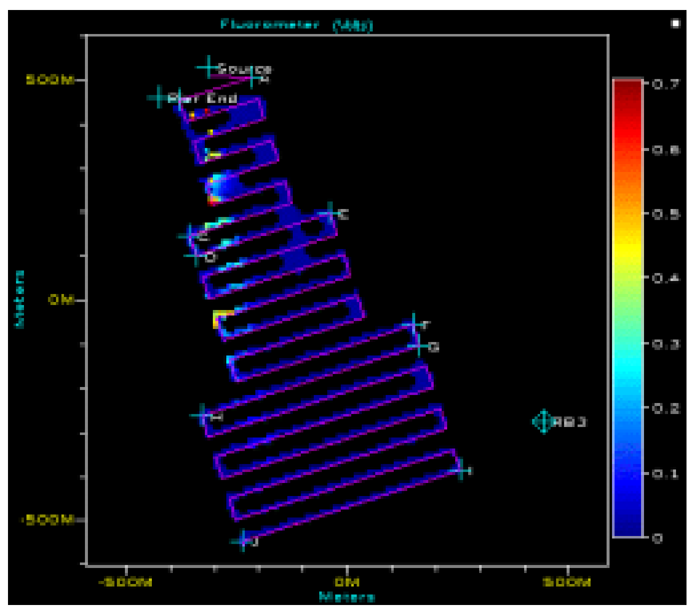

Figure 6: Full Field Run and Plume Data

The near field runs were designed to collect data on the growth phase of the plume and also to provide an efficient means of data collection on less developed plumes. Each near field run had 18 transects of the plume at progressive ranges of 5 to 90 meters from the source with a return along the same track. This was then repeated 4 times to gather additional information as to the evolution of the plume as shown in Figure 7.

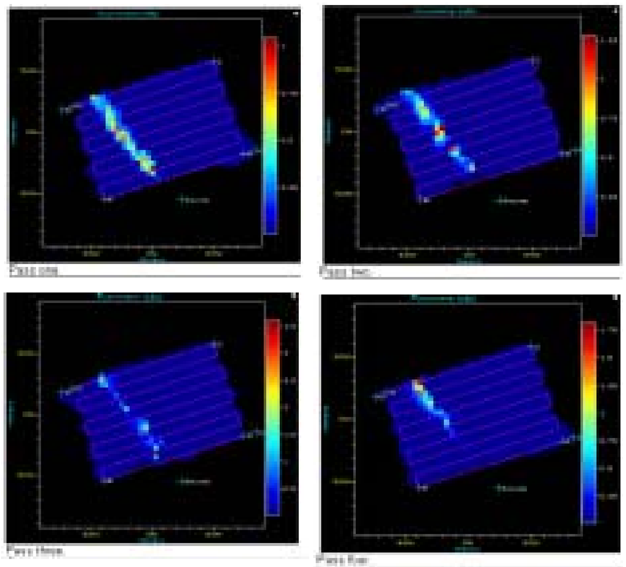

Figure 7: Near field Run showing evolution of the plume with each pass

The fixed-range type of run was a series of 40 plume crossings at a designated distance, designed to provide temporal information as to the development and evolution of the plume at a given distance [Figures 8 and 9]. These were run at distances of 150, 300, and 600 m downstream of the plume source. This data will be used in simulation studies designed to evaluate candidate sensors and analytical plume models.

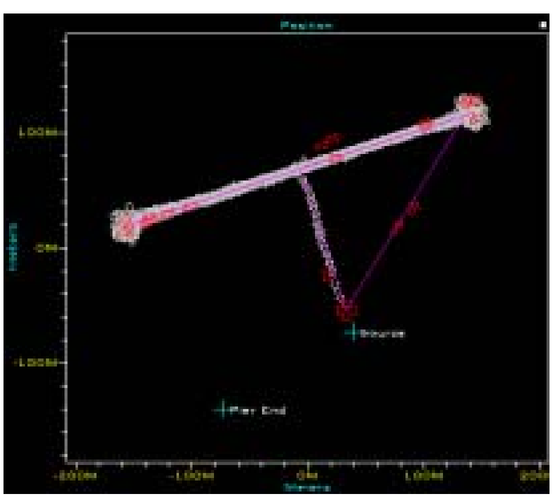

Figure 8: Fixed Range Run

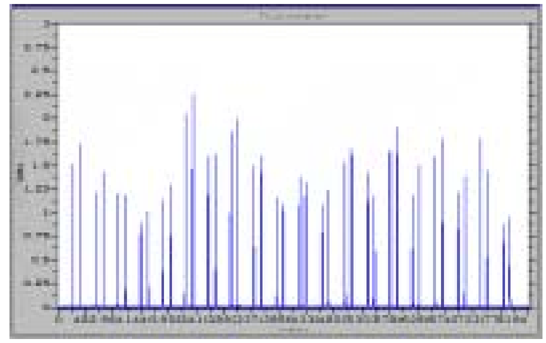

Figure 9: Fixed range plume data showing time variation of dye concentration with each pass

V. VEHICLE LESSONS LEARNED

In addition to the plume data collected, a variety of valuable lessons were learned regarding the effective operation and use of the REMUS vehicle for plume data collection.

A. Obstacle Avoidance

One of the key lessons learned at San Clemente was the necessity of careful route planning. As the REMUS does not have an obstacle avoidance capability, it is imperative to program the path to avoid the known obstacle locations as much as possible. The known topography and side scan surveys performed at Duck provided key information, allowing no time lost due to entanglements. In addition to knowing about the obstacles themselves, it is also essential to program in a sufficiently large time before timing out and aborting the mission. This allows the vehicle to make the best use of its extraction behaviors, without undue time penalty.

B. Altitude Control

For the purposes of plume analysis, it was highly desirable to collect data as close to the bottom as possible due to the bottom mounted source. The bottom tracking ADCP on the REMUS is generally limited to operating no less than 1.5 m above the bottom. To achieve this close bottom tracking, it was found best to approach the bottom gradually, in order to avoid overshooting the 1.5 m limit and losing bottom tracking altogether. By starting a run at a 3 m altitude, and gradually reducing it to the 1.5 m limit, the vehicle was able to operate successfully close to the bottom, collecting the bottom layer plume data.

C. Real Time Tracking

One of the most rewarding aspects of the Duck operations was the availability of the WHOI PARADIGM system for real time tracking of the vehicle. This is a buoy-based system which provides both the transponders for the vehicle long baseline navigation and RF modems which transmit the vehicle ranges to a shore station. Using the PARADIGM software, the vehicle track is continually displayed and logged to disk in real-time. The ability to see where the vehicle was provided both continual reassurance that the mission was proceeding as planned, and greatly facilitated the recovery process. Use of this system in San Clemente or other obstacle infested areas would greatly improve the efficiency of response to entanglements.

VI. CONCLUSIONS

The REMUS AUV has proven to be a useful asset for the collection of chemical plume data. Significantly large areas can be covered in less time and with greater resolution than with conventional towed systems. It is a versatile system which has been shown to operate effectively in a variety of environments.

ACKNOWLEDGMENTS

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